



## **DREAM2 Annual Report Program Year #2: March 2015 to March 2016**

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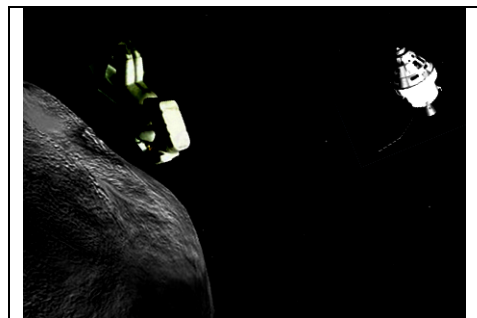
### **I. DREAM2 Team Progress Report**

The *Wargo axiom* guiding SSERVI is ‘Science enables Exploration and Exploration enables Science’. The DREAM2 corollary to this axiom is ‘The Space Environment affect Human Systems and Human Systems affect the Space Environment’. DREAM2 studies this two-way interplay of exposed bodies placed in the space environment – including human-made objects.

To pursue an understanding of this two-way space environment-object interconnection, DREAM2 gathers over 30 internationally-recognized scientists under 6 themes that are common to airless bodies: Plasma interaction, exosphere formation, radiation interaction, surface modification, effects from extreme events, and human exploration (both robotic & human missions). The scientists interact and exchange ideas advancing concepts not just within these themes, but across these themes. Modeling, mission data, and laboratory experiments are all used to advance the new cross-theme concepts – which can even lead into the development of new mission concepts like those proposed by DREAM2 team members in PY2 to PSD and AES cubesat solicitations.

In the second year, the DREAM2 team continued its unique study of the space environmental effects at exposed bodies- with an emphasis on a universal approach (different bodies, different mass, different solar wind flow, etc). We outline our stunning research achievements over the past program year in this report - some of which are also presented on the DREAM2 website (<http://ssed.gsfc.nasa.gov/dream/>).

DREAM2’s most critical element was the further development of the team’s science tasks, and PY2 year has been very successful with publication of numerous new findings (> 15



An illustration of the Orion spacecraft in the near-vicinity of the captured asteroid as planned under the ARM mission. DREAM2 team members modeled the effect spacecraft outgassing may have on the exposed body.

publications, see Section 5), a set of prestigious awards for our early career scientists (see Section 4), and engaging the public and our NASA PSD & AES leadership on the human system-space environment interactions.

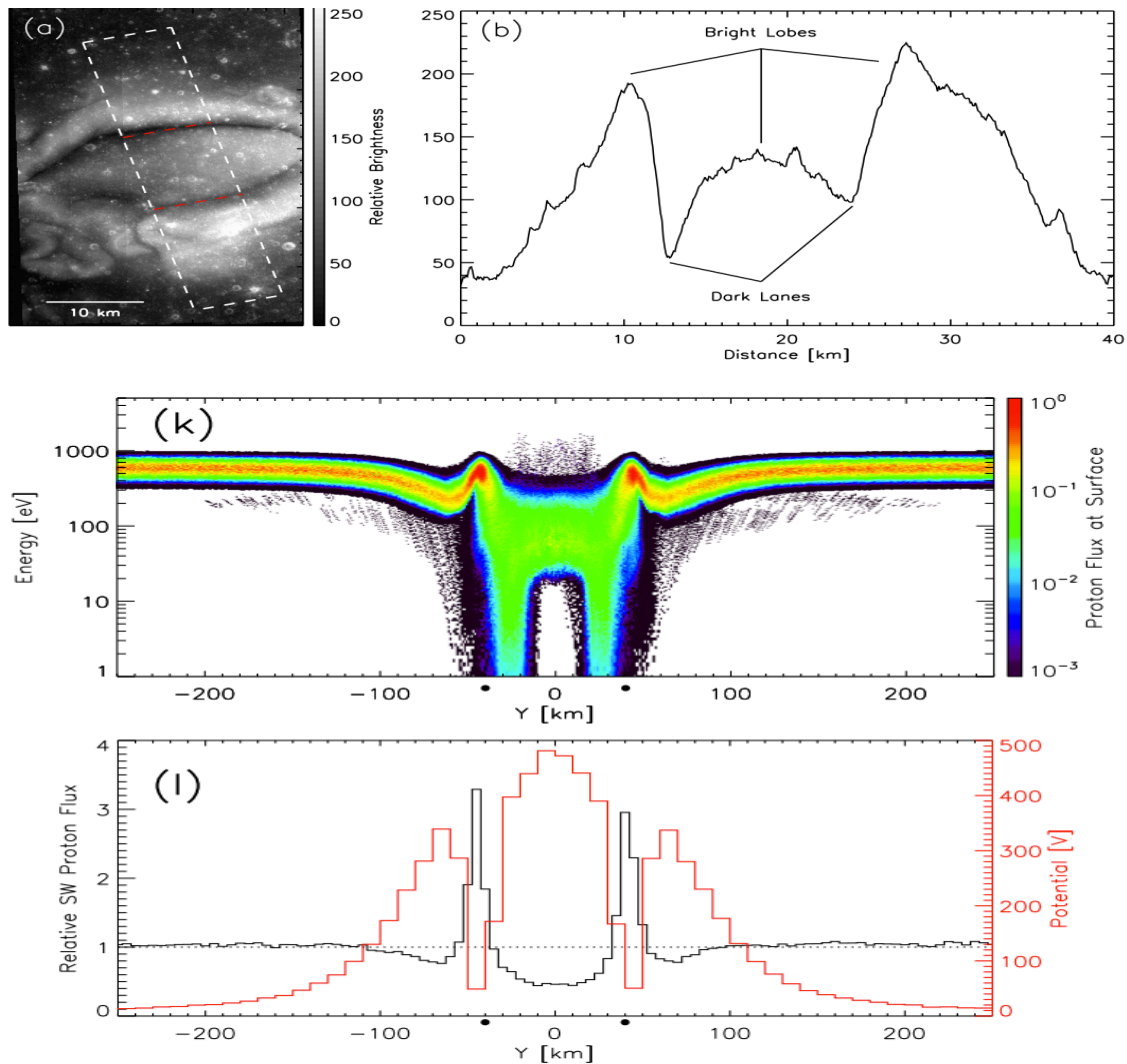
## Theme 1: Plasma Interactions with Bodies on Large to Small Scales

Every body in our solar system interfaces with a plasma, either directly at the surface, or through the envelope of an atmosphere and/or exosphere. This interaction in part mediates the coupling between solar and magnetospheric influences and the planetary surface and sub-surface. Understanding these interactions not only lays the groundwork for future exploration, but also strengthens our grasp of fundamental processes, with implications for other planetary bodies throughout our solar system and beyond.

In the past decade, our understanding of the plasma interaction with airless bodies has skyrocketed, with new observations and modeling bringing a revolution in our understanding of the Moon in particular. Whereas we once thought of airless bodies as passive absorbers of the flow, we now understand that reflected and secondary particles in fact significantly affect a region many tens of thousands of km in extent, with disturbances extending far upstream from the surface. The DREAM2 team, with its combination of simulation experts and leading experimentalists, is now working to extend that understanding to bodies of all sizes and shapes, throughout the solar system. DREAM2 team members have made the following contributions in the past year.

Plasma Interactions Topic	PY2 Advancements
Plasma Interaction vs. Body Size	Zimmerman et al. and Fatemi et al. simulations of plasma interactions with small-scale magnetic fields, Poppe/Curry Phobos simulations, Nordheim/Halekas 67P simulations, Harada/Halekas fore-moon studies.
Volatile/Plasma Connections and Exo-Ionosphere	Halekas et al. and Poppe et al. lunar exospheric ion studies, Sarantos LADEE Sodium/Potassium studies, Jordan & Stubbs breakdown weathering in lunar polar cold traps, Farrell/Zimmerman/Hurley spillage of lunar volatiles from cold traps, Farrell/Hurley solar wind implantation paper. Collier/Newheart studies using ALSEP SIDE ion measurements. Chi et al studies of pickup ion cyclotron waves.
Plasma Grounding and Electrical Interaction	Jackson & Farrell human system-plasma electrical interaction modeling. Stubbs & Hunt-Stone reanalysis of ALSEP CPLEE electron data.
Effects of Composition, Conductivity, Magnetic Field	Poppe and Fatemi swirl paper, Fatemi/Poppe/Fuqua lunar induction current modeling, Fatemi Gerasimovich paper, Sarantos et al. exospheric modeling.
Special Regions around Small Bodies	Zimmerman et al. tree-code simulations of plasma and surface charging at small irregular bodies, Poppe et al. non-aligned UV & flow paper.
Dust Around Small Bodies	Hartzell and Zimmerman plasma and dust simulations around small bodies, Poppe et al. Pluto dust paper.

We highlight a paper that exemplifies the DREAM2 spirit of exploring cutting edge science, collaborating across teams, and training young scientists. Poppe and Fatemi (a new young scientist on DREAM2) collaborated with researchers from U.C. Santa Cruz on simulations of plasma interaction with small-scale magnetic fields – not a new topic, but with a new twist. Delving into the intersection of plasma physics and geology, Poppe et al. were able to simulate the interaction for various magnetization geometries, and show that certain assumed magnetization distributions were better able to explain the observed swirl albedo markings at the famous Reiner Gamma feature, allowing us to use the observed space weathering as a new constraint on the magnetization of the crust, a quantity not uniquely determinable from magnetic field measurements from orbit.

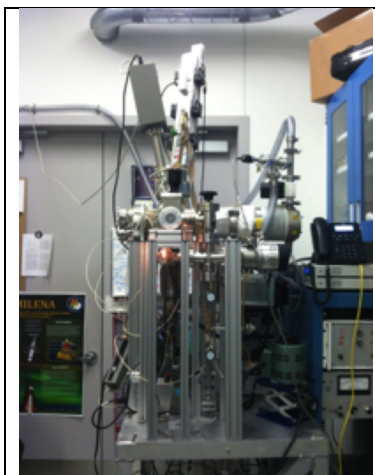


Top row shows Reiner Gamma albedo marking and a transect. Middle panel shows the simulated proton energy distribution reaching the surface. Bottom panel shows the electrostatic potential at the surface, and the proton flux. The reductions in flux create the bright lobes, and the increases in flux create the dark lanes of the albedo feature. From Poppe et al., 2016.

**JGR Cover issue:** Fatemi et al. (2015), Zimmerman et al. (2015), and Poppe et al (2015) examined the solar wind inflow into magnetic anomalies and found that the solar wind ion speed to the surface can be slowed by an ambipolar E-field that form within the anomaly retards ion motion. Some portion of the ion population is even reflected from the region. As a consequence, the associated ion sputtering yields in magnetic anomalies are vastly reduced, possibly creating reduced weathering. This work connects plasma to the extended geological environment to the surface in a rich and unique way. The Fatemi work was the cover of JGR-Planets.

## Theme 2. Exospheres and Corona at Exposed Bodies

Team exosphere has made great strides in measuring and interpreting the lunar exosphere in the past year. Lunar exospheric argon was reported from LADEE and modeled by Grava et al. (2015) and by Hodges and Mahaffy (2015), and lunar exospheric sodium and potassium also measured by LADEE were linked to meteoroid streams (Colaprete et al., 2015). Colaprete et al. (2015) used observations of sodium and potassium emission lines from the Ultraviolet and

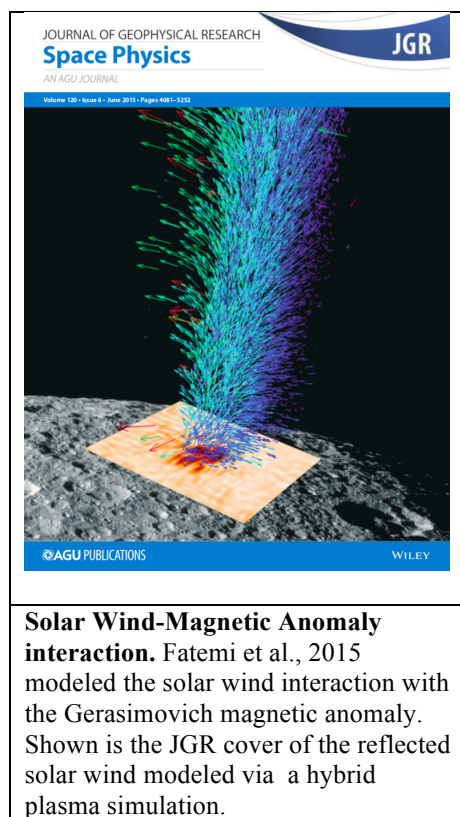


**New Adsorption Laboratory Chamber:** Regolith samples are cooled to Liquid He temperatures, there is molecular flow onto samples, and samples then heated via laser. Mass Spec monitors desorbed species.

Visible Spectrometer (UVS) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission to investigate the influence of meteoroid impacts and surface composition in determining the composition and local time dependence of the Moon's exosphere. The results showed monthly variations for both species, as well as an unexpected annual variation for sodium, which can be used to better understand the formation and evolution of exospheres on airless bodies. While the primary funding of these studies was via LADEE program, the model developments used to support the observations were funded by DREAM and DREAM2. Hence, these DREAM development efforts feed directly forward to the successful outcomes of the LADEE mission.

In addition to measuring the lunar exosphere, laboratory studies were performed to understand the physical processes involved. McLain et al. (2015) obtained preliminary measurements of desorption kinetics on silicate 'smokes', which are analogs to micro-meteoritic impact vapor condensates. The development of a new adsorption chamber was driven by the need to get fundamental data in how molecules adsorb onto regolith-like surfaces and desorb under heating. DREAM2

funded parts of this chamber along with PSD/Solar System Workings. First light on this chamber was this October and results were presented at the 'Workshop on Space Weathering at Airless Bodies' in early November (McLain, Sarantos, Keller, Nuth).

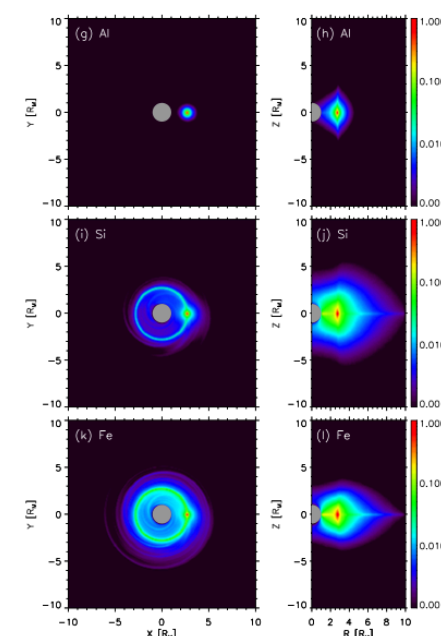




Theoretical work was done to determine the physical inputs for models. Hurley et al. (2015) fit the lunar surface temperature to an analytic function for exospheric modeling, and Killen studied pathways for breakup of simple molecules, leading to energization of the atomic fragments.

Other activity by Team Exopshere in 2015 include:

- Hurley et al, 2015 performed an analysis of the **contributions of impacts to the lunar water and hydrogen exosphere** using LAMP H<sub>2</sub> data and LADEE H<sub>2</sub>O observations. Modeling reproduces the observations of H<sub>2</sub> if micrometeoroids release the H<sub>2</sub> from the regolith. However, the abundance observed is too high to be delivered by micrometeoroids. Therefore they proposed the possibility that solar wind H is released by micrometeoroids to produce the lunar H<sub>2</sub> exosphere. Water events detected by LADEE NMS are detected with the same frequency as impacts of mass > 3 g. They suggest these events are produced by the vaporization of water delivered by the meteoroids.
- DREAM2 co-I Dana Hurley also was the lead editor of the **Icarus special issue** on lunar volatiles, featuring 18 papers (including 3 papers from DREAM2 team members).
- DREAM2 co-I Andrew Poppe and MAVEN simulation expert Shannon Curry and Shahab Fatemi continue to examine the **sputtering from Phobos** and the formation of a heavy element-rich torus about Mars associated with the Phobos-released neutrals. In their 2015 paper ( submitted JGR), they compare the sputtered vs impact vaporized portions of this torus.
- **LADEE UVS detection of a lunar nanodust exosphere.** DREAM2 members Glenar and Stubbs are collaborating with LADEE UVS team members Wooden, Cook and Colaprete on a study of weak continuum emissions detected by LADEE UVS. Light scattering models show that these measurements are consistent with sunlight scattering by an exosphere of very small dust grains. The results of this study are in the manuscript form and have been submitted for publication.



The neutral gas torus about Mars from Phobos-released neutrals (Poppe and Curry, 2014 and 2015).

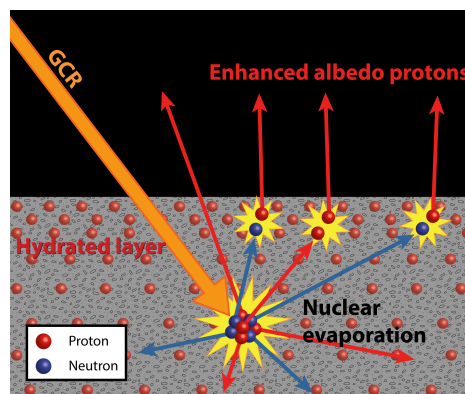
### Theme 3. Radiation interactions at Exposed Surfaces

Airless bodies like the Moon, the moons of Mars, or near earth asteroids (NEAs), are exposed to an energetic particle radiation environment that can significantly affect their surfaces. This environment comprises slowly varying, yet highly energetic galactic cosmic rays (GCRs) and sporadic, lower energy solar energetic particles (SEPs). These particles are energetic enough to penetrate the regolith of airless bodies: GCRs down to ~1 m and SEPs to ~1 mm. GCRs can eject energetic protons from lunar regolith, which can then be detected and mapped. GCRs and SEPs both deep dielectrically charge the subsurface regolith. SEPs, in particular, may create electric fields strong enough to cause breakdown (i.e., sparking).

In Program Year 2, the radiation team made significant advances in understanding the effect these energetic particles have on the surface, and even discovered a possible interaction between emitted energetic protons from water-rich surfaces.

**Energetic proton albedo brightening over hydrated mineralogy** Water on the Moon has been studied intensively for more than half a century [e.g., Lucey, 2009; Pieters et al., 2009]. Volatile accumulation in permanently shaded regions (PSRs) at the poles of the Moon has been suggested for many years, dating back to before the Apollo era [Urey and Korff, 1952; Watson et al., 1961] and beyond [e.g., Arnold, 1979]. The Lunar Prospector Neutron Spectrometer (LP-NS) utilized neutron spectroscopy to probe the lunar regolith down to depths of ~50 cm, specifically showing the high abundance of hydrogen (H) or hydrogenous species at very high latitudes where epithermal neutron emission is suppressed [Feldman et al., 1998; Feldman et al., 2001; Lawrence et al., 2006; Eke et al., 2009]. While these regions show suppressed neutron emissions, the specific association with PSRs has not been fully established and remains an important objective. The Lunar Exploration Neutron Detector (LEND) on the Lunar Reconnaissance Orbiter (LRO) subsequently provided global maps of lunar neutron fluxes [Litvik et al., 2012].

Very recently, Schwadron et al. [2015] discussed a new technique for observing hydrated material at the Moon using the energetic proton albedo [Wilson et al., 2012; Looper et al., 2013; Wilson et al., 2015]. Until recently, it has been unclear how the energetic proton albedo could be used to infer compositional signatures of the regolith. However, a key signature of latitudinal dependence in the proton albedo (increased energetic proton activity with latitude) provides continuing support for albedo proton sensitivity to hydrated material.



*Illustration of the effects of a hydrated layer of lunar regolith. If a neutron collides with a hydrogen nucleus near the surface, the collision would yield an additional “tertiary” proton. In general, the interaction of secondaries from deeper in the regolith with the hydrated layer would create an excess of albedo protons.*

The observed high latitude brighter albedo protons from a hydrated layer near the surface can be understood in terms of several steps: (1) GCRs penetrate the regolith, producing a large upward secondary neutron flux through nuclear evaporation of subsurface atoms heavier than H; (2) The collisions between upward neutrons and H in the hydrated layer causes forward scattering of protons, leading to an enhancement of albedo protons. Notably, the process requires the presence of H with a higher abundance near the surface. Otherwise, forward scattering of incident GCRs would suppress the flux of secondary protons.

Other radiation studies developed and advanced in PY2 are described in the table below.

<b>Radiation Topic</b>	<b>PY2 Advancements</b>
<b>Dielectric Breakdown Across the Lunar Surface [Jordan et al., 2015]</b>	During solar storms, airless bodies are exposed to solar energetic particles (SEPs). These particles are energetic enough to penetrate the regolith to ~1 mm and cause deep dielectric charging. In cold locations, the resulting charging may generate electric fields strong enough to cause dielectric breakdown (sparking). We have found that, in permanently shadowed regions, the fraction of gardened regolith affected (i.e., melted or vaporized) by dielectric breakdown may be comparable to that affected by meteoroid impacts [Jordan et al., submitted to <i>Icarus</i> ; see also Jordan et al., 2015a, 2015b].
<b>First directly observed longitudinal variation of radiation dose rate for a large CME event at 1 AU [Joyce et al., 2015].</b>	Solar storm energetic particle radiation dose was obtained from three different longitudinal positions in the heliosphere, which shows a large increase in dose when an observer position is directly connected to the interplanetary shock front. Such studies on positional dependence of SEP outflow relative to the solar storm front will feed forward to assessing the radiation hazards to astronauts and avoidance of said hazard.
<b>GSFC's Community Coordinated Modeling Center (CCMC) work on SEP modeling [Zheng et al.]</b>	Modeling studies of energetic particle creation in plasma shocks at they propagate outward to 1 AU. Improved coupling of SEP events to propagation models. Better-connect the physics of the interplanetary plasma shocks emitted during CMEs to the generation of energetic particles. An understanding on the creation of these hazardous energetic particles will feed forward to better warnings of their incidence during missions.
<b>Evolution of ICMEs during propagation [Winslow et al., 2015, 2016]</b>	Using multi-point spacecraft observations of interplanetary coronal mass ejections (ICMEs), we study their propagation and evolution in the inner heliosphere in order to better predict their influence on planetary environments. In Winslow et al. [2015], we cataloged ICME events observed by the MESSENGER Magnetometer between 2011 and 2014 and presented statistical analyses of ICME properties at Mercury. In addition, using existing data sets of ICMEs at 1 AU, we investigated key ICME property changes from Mercury to 1 AU. We found good agreement with previous studies for the magnetic field strength dependence on distance, and we also found evidence that ICME deceleration continues past the orbit of Mercury. This study leads to a greater understanding of CME and shocks, and the potency of these storms in creating energetic particles that affect humans.
<b>Updates to the Virtual Energetic</b>	Enhanced capability of VEPO. Created Multi-Source Spectral Plot, Scatter Plot, and Ratio Plot services now provided for energetic particle data from

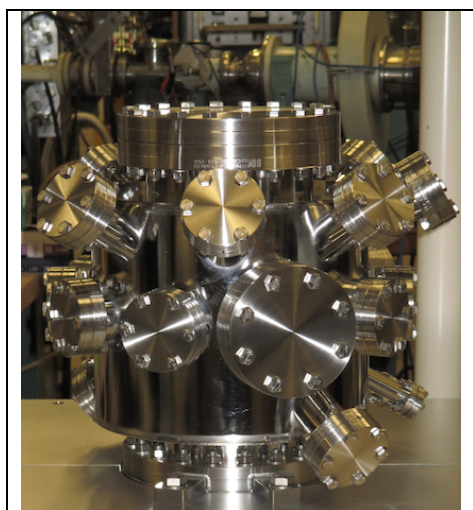
<b>Particle Observatory (VEPO) [Cooper].</b>	operational inner heliospheric spacecraft (ACE, Wind, SOHO, Stereo A/B) and legacy missions (Helios 1-2, IMP-8, Pioneer 10-11, Voyager 1-2, Ulysses). Full coverage for H and/or He ions, partial to full coverage for H – Ni ions. New abilities also include: (1) Inter-comparison of flux spectra from different spacecraft and instruments allows checking of relative calibrations for overlapping energy coverage. (2) Mission-duration average flux spectra can be used to model long-term space weathering of planetary bodies in the inner and outer solar system. (3) Multiple spacecraft spectral H-Ni response to large scale SEP eventsDual channel fluxes can be sequentially searched for special features, e.g. Fe/He SEP events, energy dispersion in low vs high energy electrons. VEPO collaborates with DREAM-2 in providing these data exploration services and in receiving feedback guiding development of future VEPO services.
<b>Solar Modulation of the GCR Lineal Energy Spectrum [Zeitlin et al., 2016]</b>	The long period of CRaTER observations allows us to study the evolution of these spectra as a function of solar modulation. As solar modulation increases, the total flux of GCRs decreases, and lower-energy ions are preferentially removed from the spectrum of ions that arrive in the inner heliosphere. These effects lead to variations in the Linear Energy Transfer spectrum, which is used to determine dose, dose equivalent, and risk to humans in space. The results are also of interest in the context of the DREAM2 project, which advances understanding of the galactic and solar radiation environments at the target bodies (including the Moon), emphasizing material interaction/reactions due to incident high energy particles. Understanding the LET spectrum and its evolution with time is important for characterizing the radiation environment and helps investigators understand the effects of high energy particles on target bodies. This work will be presented at the upcoming HRP meeting in Feb 2016.

Table: Radiation-oriented DREAM2 studies in PY2.

#### Theme 4: Surface Response to the Space Environment

As the harsh elements of space, like impactors and plasma, interact with the surface, their energy leaves a modifying signature on the surface structure. For example, space plasmas will disrupt the regolith crystal structure in the first 100 nm, creating defects that can trap solar wind protons and ‘hopping’ water or OH on the airless body. Radiation alters the surface by creating streaking defects and charge buildup which also may be sites for solar wind hydrogen trapping.

To test this, DREAM2 is completing the building of a dual-irradiation lab experiment in GSFC’s radiation facility. We will first irradiate a sample surface with high energy radiation ( $> 1$  MeV) to create defects in the material, then perform (under the same vacuum) a second irradiation of the sample by 1 keV  $D_2$  or protons that simulate the solar wind protons. We will determine if the



Chamber placed at end of beam line for sample dual irradiation experiments.



additional **defects from the high energy radiation traps H (or D) and creates OH (or OD)**. The beam line is complete and the team is currently placing their newly procured chamber (see adjacent figure) onto the line (Loeffler, Hudson, McClain, Keller).

Other surface interaction studies include:

- **Hydrogen diffusion in a defected regolith.** Summer Intern Vince Esposito from Univ. of South Carolina worked with DREAM's Farrell in integrating TRansport of Ions into Matter (TRIM) code results into an existing hydrogen diffusion model developed in PY1 of DREAM (and published Farrell et al., 2015). The objective was to create a more realistic distribution of activation energy representative of a surface that has been damaged by space plasmas. The diffusion of solar wind implanted H was then modeled using the damaged surface, now having a population of high-retention trapping sites. The work was presented at the *'Workshop on Space Weathering at Airless Bodies'* in early November (Esposito, Farrell, Zimmerman)
- **Neutral Hydrogen emission from the lunar surface.** In the lab, a GSFC team (McLain, Keller, Collier) are examining solar wind-like 1 keV proton interactions with lunar-like surface material, demonstrating that a surprisingly large fraction of the incoming ions convert and backscatter as energetic neutral hydrogen. They leave the surface at energy far greater than simple thermal energy –suggesting these H's do not dwell in the surface and undergo numerous collisions but instead are immediately scattered from the first nucleus they encounter.
- **Transport of lunar polar crater volatiles to topside regions via impact vaporization and plasma sputtering.** A model of the removal and transport of volatiles from lunar polar crater floors was published this program year, demonstrating that impact vaporization and sputtering are continually weathering crater floors and liberating volatiles to topside regions adjacent to the craters (Farrell, Hurley, Zimmerman).
- **Orion water outgassing and water retention on the asteroid boulder.** DREAM2 investigators (Farrell, Hurley, Zimmerman) submitted a paper to Icarus on the Orion-asteroid body interaction expected during the ARM mission. Water may be retained on the asteroid surface, depending upon the defect character, maturity, and composition of the boulder. Estimates of the Orion water retention levels were provided.
- **Oak Ridge Mutli-charged ion sputtering on CaS surfaces** (Meyer, Bannister, Hihazi). The lab team at ORNL bombarded CaS substrates with solar wind relevant multi-charged ions to examine the sputtering yields. On Mercury, very hot Ca has been observed (as reported by DREAM2 co-I Killen) which is believed to be associated with a possible exothermic reaction providing energy to dissociating products. The ORNL study begins to examine these effects in a lab environment.
- **Dust cohesion.** Dust expert J. Marshall has been investigating how dust and sand respond to transport forces, abrasion, tribocharging, and cohesion in airless or near airless Solar System environments with relevance to understanding fundamental physical processes as well as the response of airless body surfaces to contacts with astronauts or mechanical objects. Some controversial results have been found and are to be submitted to the journal *Planetary & Space Sci.* in early 2016.

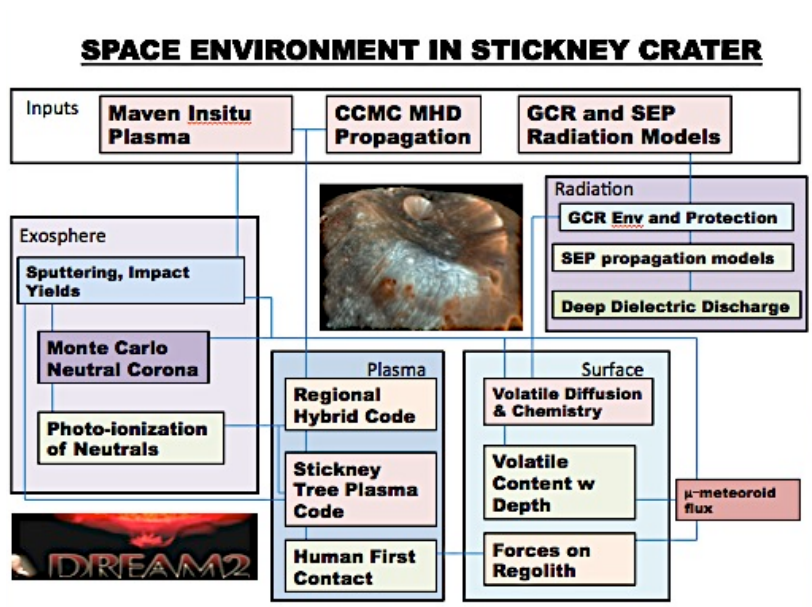
## Theme 5: Integration and Extreme Events

In the upcoming last three years of DREAM2, the team plans to have a coordinated modeling efforts on the effect of extreme environments at small bodies and the Moon. This effort is called the DREAM2 Extreme Environment Program (DEEP). In this program, our models will be integrated to be run in a given sequence on a common event. This activity is similar to our 2010 SSLAM (Solar Storm- Lunar Atmosphere Model) effort under DREAM.

The three DEEP studies are 1) The effect of a solar storm at an exposed small body, 2) The space environment in Phobos' Stickney Crater, and 3) Human 'first contact' with a small body/NEA. This past year, the decision was made to proceed with a study of the space environment at Phobos and Stickney Crater (SEinSC). We spent the fall of 2015 laying out what such a study would look like including an information flow diagram (see below), showing how spacecraft and model plasma data flows down to the various models, how models are cross-connected and how model output information is exchanged.

Our plan is to hold a dedicated intramural workshop in the third week in April 2016 to show new results and fine-tune the cross connections.

Progress made so far: Fatemi's hybrid simulation of solar wind influences and effects at Mars has been developed. Model output will feed forward to a particle in cell code developed by Mike Zimmerman of Phobos itself, where the detailed sheath and wakes at the body can be modeled as a function of plasma conditions in the Martian tail. We have access to MAVEN data and GSFC's Community Coordinated Modeling Center (CCMC) possesses model CME events to Mars (used previously for comparisons with MAVEN data).



System-Level Block Diagram of the 'Space Environment in Stickney Crater' Modeling Study

## Theme 6: Mission and Exploration Applications

DREAM2's team continues to have broad and deep involvement in both SMD and HEOMD missions and studies. The most active involvement includes:

**The Lunar Atmosphere and Dust Environment Explorer (LADEE).** LADEE concluded operations in April 2014 and continued on in an extended data analysis phase through Oct 2015. DREAM2 Co-Is Colaprete, Delory, and Elphic all continued to be involved in the LADEE mission during this phase. Rick Elphic was the project scientist; Greg Delory was the Deputy project scientist, and was responsible for submission of the final derived data products to the PDS. A. Colaprete completed data submission for the UVS instrument. DREAM2 Co-Is Halekas, Poppe, Hurley, Stubbs, Sarantos, and Glenar continued to work with LADEE as Guest Investigators through the end of the data analysis phase.

**Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS).** As LADEE Guest Investigators, DREAM2 Co-Is Halekas and Poppe have sustained a productive collaboration between LADEE and ARTEMIS. Along the way they have pioneered unique methods to support the interpretation of LADEE data using coincident measurements of lunar pick-up ions and the lunar plasma environment. Poppe has been using ARTEMIS data of pick-up ions to assist in understanding the currents levels in the LADEE/LDEX dust current system – to differential pick-ion currents from dust currents. Halekas has also used ARTEMIS pick-up ion observations to assist in the LADEE/NMS sensing of this component in its ion mode. A paper has been written in this joint ARTEMIS-LADEE analysis. These measurements have had measurable impact on both LDEX and NMS data processing. Hurley, Halekas et al have used ARTEMIS data of solar wind helium ion (alpha particle) flux to correlate with the LADEE/NMS and LRO/LAMP detection of surface-emitted exospheric helium. The correlation is stunning revealing that the helium exosphere is mostly solar wind driven, but with a possibly smaller geological residual. Additional work by DREAM2 Co-I Delory is using two of the ARTEMIS spacecraft in a study of induced magnetic fields at the Moon. This work also involved significant graduate student involvement (H. Fuqua), who won the outstanding student poster award at the 2015 SSERVI forum (see Section IV).

**ARM Mission.** DREAM2 members continue to be involved in ARM studies through investigations into astronaut charging. DREAM2 member Joseph Nuth is a member of the ARM Formulation, Assessment, and Support Team (FAST). The DREAM2 team has a paper in submission to Icarus on the Orion-Asteroid gas interaction.

**Resource Prospector (RP).** With FINESSE team members, DREAM2 co-is Elphic and Colaprete are instrument leaders of the HEOMD-funded RP mission to explore and prospect the lunar polar regions for volatiles. DREAM2 has contributed to this effort by providing models of volatile transport and redistribution that identify locations where RP might prospect. Models of rover wheel charging are also applicable to the RP rover system. The wheel charging model was presented at the recent lunar *Polar Regolith Workshop* (a SSERVI Workshop without Walls) held by SSERVI in early December 2015.

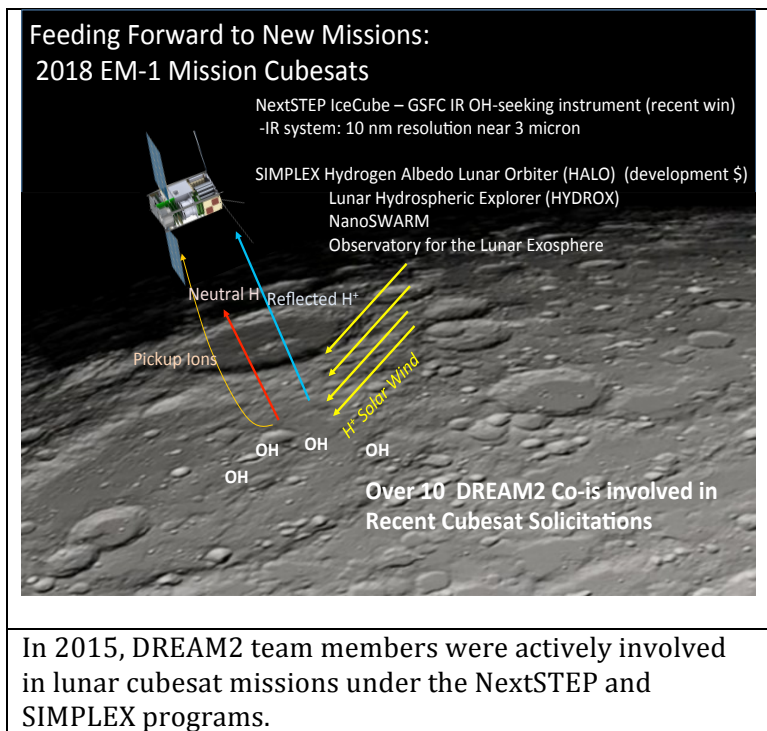
**OSIRIS-REx.** DREAM2 team member Joseph Nuth is the deputy project scientist on OSIRIS-Rex. Team member Marshall is the leader of the OSIRIS Regolith Working Group (RWG) and his dust cohesion work (described above) has direct implications on regolith stability anticipated at any small asteroid, including Bennu.

**LRO.** DREAM2 team members continue to support LRO. DREAM2 co-is Keller is the Project Scientist on the LRO Project Science team and there is continual DREAM2/LRO discussion on the latest finding especially on volatiles. Team member Nathan Schwadron is the

PI of the CRaTER instrument on LRO, with Andrew Jordan as part of the CRaTER science team. Dana M. Hurley remains a Co-Investigator on the LRO LAMP instrument. Team member Andrea Jones continues to support EPO on LRO. Tim Stubbbs continues his Guest Investigator role with the CRaTER team.

**Additional Discovery and other mission proposals.** Many DREAM2 Co-Is have had significant involvement in emerging mission proposals ranging from Discovery to cubesat-class that involve the physics of small-body/solar wind and plasma interactions.

Team members Poppe and Delory were Co-Investigators on the Discovery-class PADME mission to study Phobos and Deimos lead by ARC team members Colaprete and Elphic.



**Cubesats.** DREAM2 team members were very actively involved in new lunar mission concepts using cube-sats – especially those released during the 2018 EM-1 mission. Co-I Clark was the science PI of the awarded Lunar Icecube cubesat mission headed by Morehead State University and funded under the AES NextSTEP program. DREAM2 team members also submitted numerous strong cubesat concepts to PSD’s SIMPLEX solicitation, including the Hydrogen Albedo Lunar Orbiter (HALO) concept (Collier, Keller, Farrell, Vondrak) that was awarded development funding, the Lunar Hydrospheric Explorer

(HYDROX) proposal (Cooper, Stubbs, Sarantos), NanoSWARM (Poppe, Fatemi), and Observatory for the Lunar Exosphere (OLE) (Sarantos).

Team members at GSFC lead (Collier, Vondrak, Keller, Farrel, Clark) have also been examining the feasibility of a tethered cubesat to obtain 2- point radial measurements.

DREAM2 Co-I Clark continues the lead the community the Lunar Cubesat workshops which are has held annually over the last 6 years. These efforts are specifically designed to enable the community in anticipation of planetary cubesat proposal calls, like the recent SIMPLEX solicitation.

Team member Dana Hurley, as leader of the Friends of Lunar Volatiles group, contributed to exploration efforts by developing and submitting a **white paper on lunar polar volatiles** to the leadership of HEOMD – this to inform on the current state of knowledge.



## **II. Inter-team Collaborations**

DREAM2 team members are in continual contact and collaboration with other SSERVI teams, science mission team, and Exploration architecture teams. Examples of DREAM2 interactions with other SSERVI teams include:

**VORTICES:** Strong collaborating work on solar wind/body interactions, volatile interactions, and Orion/asteroid interactions and lunar pits. Strongest collaborations with individuals like Zimmerman, Hurley, Bussey, Orlando, Hibbitts.

**RISE4:** Strong collaborating work on lunar pits, with the RISE4 field team providing lidar input to pit environment models shared by DREAM2 and VORTICES. Work with RISE4 team to pursue opportunities to architecture, design and build future exploration-oriented field instrumentation for astronaut use.

**IMPACTS:** PIs Hornayi and Farrell co-lead the SSERVI Dust and Atmosphere Focus Group. Strong cross-team collaboration including post-doc opportunities for students, like A. Poppe who did his thesis work under CCLDAS and is now a key DREAM2 team member. DREAM2 modelers working with IMPACTS modelers on magnetic anomaly studies.

**FINESSE:** We share co-PIs in Colaprete and Elphic, who under FINESSE perform field studies for their Resource Prospector mission, while DREAM2 provides supporting modeling studies on wheel-regolith interactions and volatile transport modeling.

### III. Public Engagement Report

Summer 2015 marked another successful undergraduate internship program, with DREAM2 scientists at GSFC hosting four students, including one from DREAM2 partner, Howard University. In addition to completing their research projects, the students participated in monthly team meetings, tours of GSFC facilities, and a heliophysics boot camp. At the end of the summer, they presented their completed projects through poster and oral presentations that were open to the entire GSFC community and their families. While at GSFC, two DREAM2 interns were named John Mather Nobel Scholars via a competitive process. The program awards travel allowances towards the cost of presenting research papers at professional conferences. The two students also continued their DREAM2 research into the academic year.



The DREAM2 education and public engagement team implemented the Dream2Explore Educator Professional Development Workshop, which brought 23 middle school educators to GSFC for an in-depth week of hands-on activities, discussions, presentations by five DREAM2 scientists and others, tours, and networking opportunities with DREAM2 scientists. Content focused on SSERVI target bodies: formation, comparing/contrasting structure and composition of surfaces and exospheres, effects of space weather, engineering design challenges, NASA's current plans to explore asteroids and the "Journey to Mars". 100% of the participants agreed that they acquired activities that they will use with their students. 91% agreed that they feel confident in implementing the activities and that they acquired a new understanding of planetary science and exploration that will be valuable when working with their students.

Participant quotes: *"The workshop improves my class and the kids' learning. That's what it's intended to do!"*; *"I gain useful information for the classroom and feel comfortable using it since I have done it."*; *"I really value learning new material as a teacher – if I learn new things... the students learn new things. I learned a lot here – Thank you!"*; *"This is the only experience that as a teacher I have an opportunity to connect with scientists."*

DREAM2 team members also shared information about DREAM2 and SSERVI at public engagement events, such as the University of Maryland's annual Maryland Day event, International Observe the Moon Night at the Andrews Air Show, and GSFC's open house "Explore@NASA Goddard". Each event drew crowds in the tens of thousands.

#### **IV. Student/Early Career Participation and Associated Awards**

##### 2015 Undergraduate Summer Interns

Anastasia Newheart, St. Marys (1)  
Keenan Hunt-Stone, Howard Univ. (2)  
Vince Esposito, Univ of South Carolina (3)  
Tatiana Tway, Delaware Valley Univ.  
Huong Vo, Univ. of Washington

##### 2015 High School Summer Interns

Aparna Natarajan, Wooton HS  
Zoe Himwich, Bethesda-Chevy Chase HS

##### Graduate Students

Heidi Fuqua, UC Berkeley (4)  
Colin Joyce, U. New Hampshire

##### DREAM2 Post-Docs

Shahab Fatemi, UC Berkeley  
Reka Wilson, U. New Hampshire

##### DREAM2 Student awards:

(1) A. Newheart: John Mather Nobel Scholars Award  
(2) K. Hunt-Stone: John Mather Nobel Scholars Award  
(3) V. Esposito: Robert H. Goddard Memorial Scholarship from National Space Club  
(4) H. Fuqua: Outstanding Grad Student Poster Award at SSERVI Exploration Science Forum

## **V. DREAM2 Papers in PY2**

- Jackson, T. L., W. M. Farrell, M. I. Zimmerman (2015), Rover wheel charging within a lunar crater, *Adv. Space Res.* 55, 1710-1720 , **SSERVI-2014-168**
- Fatemi, Shahab, Charles Lue, Mats Holmstrom, Andrew R. Poppe, Martin Wieser, Stas Barabash, and Gregory T. Delory (2015), Solar wind plasma interaction with Gerasimovich lunar magnetic anomaly, *J. Geophys. Res.*, 120, 4719-4735 . **SSERVI-2015-026**
- Farrell, W. M., D. M. Hurley, and M. I. Zimmerman (2015), Solar wind implantation into lunar regolith: Hydrogen retention in a surface with defects, *Icarus*, 255, 116-126. **SSERVI-2014-010**
- Lipatov, A. S., W. M. Farrell, J. F. Cooper, E. C. Sittler, and R. E. Hartle (2015), 3-D hybrid kinetic modeling of the interaction between the solar wind and lunar-like exospheric pickup ions in the case of oblique/quasi-parallel/parallel upstream magnetic field, *Planet. Space Sci.*, submitted, **SSERVI-2015-041**
- Farrell, W. M., D. M. Hurley, and M. I. Zimmerman (2015), Spillage of lunar polar crater volatiles onto adjacent terrains: The case for dynamic processes, *Geophys. Res. Lett.*, 42, 3160-3165, **SSERVI-2015-042**
- Zimmerman, M. I., W. M. Farrell, A. R. Poppe (2015), Kinetic Simulations of Micro-Magnetosphere Formation on the Moon, *J. Geophys Res.*, 120, 1893-1903, **SSERVI-2015-159**
- Fatemi, S., H. Fuqua1, A. R. Poppe, G. T. Delory, J. S. Halekas, W. M. Farrell and M. Holmstrom (2015), On the confinement of lunar induced magnetic fields, *Geophys. Res. Lett.*, 42, 6931-6938, **SSERVI-2015-161**
- Poppe, A. R., S. Fatemi, I. Garrick-Bethell, D. Hemingway, and M. Holmstrom (2016), Solar wind interaction with the Reiner Gamma crustal magnetic anomaly: Connecting source magnetization to surface weathering, *Icarus*, 266, 261-266, **SSERVI-2015-160**
- Halekas, J. S. ,M. Benna, P. R. Mahaffy, R. C. Elphic, A. R. Poppe, and G. T. Delory (2015), Detection of lunar exospheric ions by the LADEE Neutral Mass Spectrometer, *GRL*, Submitted, **SSERVI-2015-185**
- Jordan, A. P., T. J. Stubbs, J. K. Wilson, N. A. Schwadron, and H. E. Spence (2015), Implications of the rate of dielectric breakdown weathering of lunar regolith in permanently shadowed regions, *Icarus*, submitted, **SSERVI-2015-186**.
- Schwadron, N. A., J. K. Wilson, M. D. Looper, A. Jordan, H. E. Spence, J. B. Blake, A. W. Case, Y. Iwata, J. Kasper, W. Farrell, D. J. Lawrence, G. Livadotis, et al. (2015), Possible albedo proton signature of hydrated lunar surface later, *Icarus*, submitted. **SSERVI-2015-187**.



- Wilson, J. K., N. Schwadron, H. E. Spence, J. B. Blake, A. W. Case, A. P. Jordan, J. Kasper, M. D. Looper, N. E. Petro, M. S. Robinson, S. S. Smith, T. J. Stubbs, L. W. Townsend, C. Zeitlin (2015), Localized features in the albedo proton map of the Moon, Icarus, submitted, **SSERVI-2015-188**.
- Poppe, A. R., S. M. Curry, and S. Fatemi, The Phobos neutral and ionized torus, J. Geophys. Res., submitted. **SSERVI-2016-003**.
- Collier, M. R., R. R. Vondrak, R. P. Hoyt, M. A. Mesarch, W. M. Farrell, J. W. Keller, P. E. Clark, N. E. Petro, and K.-J. Hwang, Tethered lunar subsatellites for multi-point and low altitude measurements, J. Spacecraft Rockets, submitted. **SSERVI-2016-004**.
- Farrell, W. M., D. H. Hurley, M. J. Poston, M. I. Zimmerman, T. M. Orlando, C. A. Hibbitts, and R. M. Killen (2016), The Gas-Surface Interaction of a Human-Occupied Spacecraft with a Near Earth Object, Icarus, submitted. **SSERVI Number Pending**
- Joyce, C. J., Schwadron, N. A., Townsend, L. W., Mewaldt, R. A., Cohen, C. M. S., Rosenvinge, T. T., Case, A. W., Spence, H. E., Wilson, J. K., Gorby, M., Quinn, M., and Zeitlin, C. J. (2015), Analysis of the potential radiation hazard of the 23 July 2012 SEP event observed by STEREO A using the EMMREM model and LRO/CRaTER, Space Weather, 13, 560. **SSERVI Number Pending**
- Hodges, R.R. and P.R. Mahaffy (2016), Synodic and semiannual oscillations of Argon-40 in the lunar exosphere, Geophys. Res. Lett. 43, doi:10.1002/2015GL067293. **SSERVI Number Pending**